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RESEARCH MEMORANDUM

EFFECT OF THREE FLAME-HOLDER CONFIGURATIONS ON SUBSONIC FLIGHT PERFORMANCE OF RECTANGULAR RAM JET OVER RANGE OF ALTITUDES

By Dugald O. Black and Wesley E. Messing

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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RESEARCH MEMORANDUM

EFFECT OF THREE FLAME-HOLDER CONFIGURATIONS ON SUBSONIC FLIGHT PERFORMANCE OF RECTANGULAR RAM JET OVER RANGE OF ALTITUDES

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SUMMARY

A flight investigation has been conducted on a rectangular ram jet over a range of fuel-air ratios from 0.017 to 0.120, combustion-chamber-inlet velocities from 50 to 125 feet per second, and pressure altitudes from 1500 to 28,000 feet.

A comparative study is presented to determine the effects of altitude, combustion-&ember-inlet velocity, and fuel-air ratio on starting characteristics, minimum blow-out limits, combustion efficiency, gas total-temperature ratio, and net-thrust coefficient for three flame holders of similar design but different ratios of flame-holder area to combustion-chamber area.

At all altitudes, combustion efficiencies for the three-V flame holder, which varied from a maximum of 82 percent at 1500 feet to 39 percent at 26,000 feet, were slightly higher than the efficiencies obtained with the two-V and four-V flame holders. Higher combustion efficiencies were obtained with the two-V flame holder than with the four-V flame holder. The highest gas total-temperature ratio (7.10) occurred at 6000 feet when the ram jet was operating at a fuel-air ratio of 0.082 with the three-V flame holder. The highest net-thrust coefficient was obtained with the two-V flame holder and the lowest values were obtained with the four-V flame holder at any given altitude and fuel-air ratio. In general, increasing the flame-holder area increased the value of fuel-air ratio at which ignition occurred and decreased the maximum altitude at which ignition was possible for a given airspeed.

INTRODUCTION

As part of an extensive study on ram jets as aircraft propulsive power plants, flight investigations are being conducted at the NACA Cleveland laboratory on a wing-type, rectangular ram jet installed

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beneath the fuselage of a twin-engine, fighter-type airplane. During a test-stand investigation (reference 1), a similar engine was satisfactorily operated over a range of fuel-air ratios from 0.025 to 0.083. The performance and operational characteristics of the wing-type ram jet were determined in flight over a range of altitudes for one flame-holder design (reference 2).

Two additional flame holders of similar design, but having a lower ratio of flame-holder area to combustion-chamber area, were investigated over a range of fuel-air ratios from 0.017 to 0.120, combustion-chamber-inlet velocities from 50 to 125 feet per second, and pressure altitudes from 1500 to 28,000 feet to determine the change in performance and operational characteristics of the engine. A comparative study to determine the effects of altitude, combustion-chamber-inlet velocity, and fuel-air ratio on starting characteristics, minimum blow-out limits, combustion efficiency, gas total-temperature ratio, and net-thrust coefficient for the various flame-holder configurations is presented.

APPARATUS AND PROCEDURE

The wing-type, rectangular ram jet was supported by streamlined struts beneath the fuselage of a twfn-engine, fighter-type airplane, as shown in figure 1. A schematic diagram of the ram jet giving all the main dimensions is shown in figure 2. The ram jet is more fully described in reference 2.

The combustion chamber was cooled and the fuel was preheated by introducing the fuel at the rear of the ram jet and circulating it under pressure through a corrugated manifold, which was seam-welded to the combustion chamber, to a common fuel-spray bar. The fuel-spray bar, located along the horizontal center line of the diffuser, contained six evenly spaced nozzles, each rated at 40 gallons of fuel per hour at a fuel pressure of 100 pounds per square inch. The fuel used in this investigation was 73-octane gasoline (AN-F-23a). Ignitionwas initiated by a converted aircraft sparkplug. Tufts were mounted on the top and bottom walls of the diffuser just forward of the flame holder in order to determine whether combustion advanced upstream of the flame holder to the fuel-spray nozzles.

The three flame-holder configurations investigated (fig. 3) consisted of seventeen vertical and two, three, and four horizontal V-shaped gutters, and were fabricated from 0.064-inch Inconel. The ratios of flame-holder area to combustion-chamber area and the measured $\frac{p_2-p_4}{q_2}$ values (where p_2 is static pressure at diffuser outlet, p_4 is static pressure at combustion-chamber outlet, and q_2 is dynamic pressure at diffuser outlet) without combustion are:

Flame holder (number of horizontal gutters)	$\frac{\text{Flame-holder area}}{\text{Combustion-chamber area}}$	$\frac{p_2-p_4}{q_2}$
2	0.49	2.3
3	.55	2.6
4	.60	3.1

These flame-holder configurations are herein designated two-V, three-V, and four-V flame holders.

Engine air flow was calculated from total and static pressures measured at the diffuser inlet by three total- and static-pressure rakes and eighteen static-pressure wall orifices and from the free-air temperature, which was indicated by an iron-constantan thermocouple installed. tier the left wing of the airplane. Fuel flow was measured by a vane-type flowmeter. Total and static pressures at the combustion-chamber outlet were measured by a water-cooled total-pressure rake and two static-pressure wall orifices. Aircraft indicators were used to obtain indicated airspeed and altitude as measured by a swiveling static-pressure tube and a shrouded total-pressure tube installed on a boom 1 ohord length ahead of the leading edge of the right wing tip. The complete instrumentation is described in reference 2.

Most of the combustion data were obtained for each flame holder at pressure altitudes of 1500, 6000, 16,000, and 26,000 feet. In order to obtain similar flight conditions for the three flame holders, the investigations were conducted at a constant indicated airspeed of 200 miles per hour at altitudes of 1500, 6000, and 16,000 feet. At an altitude of 26,000 feet, the operating range of fuel-air ratio was so narrow that the indicated airspeed was decreased from 200 to 160 miles per hour in order to obtain sufficient data for comparative purposes. Starting characteristics were obtained over a range of pressure altitudes from 1500 to 28,000 feet, and indicated airspeeds of 105 to 200 miles per hour.

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SYMBOLS

The following symbols are used in this report:

A	combustion-chamber cross-sectional ares, square feet
A_{max}	maximum combustion-chamber cross-sectional area, 1.84 square feet
C_F	net-thrust coefficient
F_n	net thrust, pounds
f/a	fuel-air ratio
g	acceleration due to gravity, 32.17 feet per second per second
H_a	enthalpy of air and fuel before combustion, Btu per pound of original air
H_g	enthalpy of burned gases at exhaust-gas temperature, Btu per pound of original air
h_f	lower heating value of fuel, 18,508 Btu per pound
m_a	mass air flow, slugs per second
m_g	mass exhaust-gas flow, slugs per second
P	total pressure, pounds per square foot absolute
p	static pressure, pounds per square foot absolute
q	dynamic pressure, pounds per square foot
R	gas oonstant, foot-pounds per °F per pound
T	total temperature, °R
V	velocity, feet per second
γ	ratio of specific heat at oonstant pressure to specific heat at constant volume
η_b	combustion efficiency, percent
τ	gas total-temperature ratio, ratio of exhaust-gas temperature T_4 to ambient-air temperature T_0

Subscripts:

0 equivalent free-stream condition

1021 1 diffuser inlet

2 diffuser outlet (in front of flame holder)

4 combustion-chamber outlet

METHOD OF CALCULATIONS

The exhaust-gas temperature T_4 was calculated from the measured gas flow at the combustion-chamber outlet according to the following equation:

$$T_4 = \left(\frac{p_4{}^2 A_4{}^2}{g R_4 m_g{}^2}\right) \frac{2\gamma_4}{\gamma_4 - 1} \left[\left(\frac{P_4}{p_4}\right)^{\frac{\gamma_4-1}{\gamma_4}} - 1\right] \left(\frac{p_4}{P_4}\right)^{\frac{\gamma_4-1}{\gamma_4}}$$

The combustion efficiency η_b was determined by the equation

$$\eta_b = \frac{H_g - H_a}{f/a(h_f)} 100$$

The net-thrust coefficient C_F was calculated according to the following equation:

$$C_F = \frac{F_n}{q_0 A_{max}}$$

where

$$F_n = m_g V_4 - m_a V_0 + A_4 (p_4 - p_0)$$

RESULTS AND DISCUSSION

Visual observations were similar to those reported in reference 2; that is, at altitudes of 1500 and 6000 feet, the exhaust flame extended approximately 1 foot beyond the engine outlet and wee light blue at stoichiometric fuel mixtures. Increasing the fuel-air ratio increased the flame length and the color became yellow because of afterburning of the excess fuel. An increase in altitude decreased the visibility of the flame and above 16,000 feet the flame was no longer visible even at rich fuel-air ratios. No noticeable difference in flame length or oolcr was observed for the different flame-holder configurations when operating at similar conditions. 1021

Rough engine operation was encountered at an Indicated airspeed of 200 miles per hour at all altitudes with the two-V flame holder as the fuel-air ratio approaohed the lean blow-out limit. The same condition was observed with the three-V flame holder at and above 6000 feet and with the four-V flame holder at and above 16,000 feet. Rough engine operation was also encountered at fuel-air ratios above 0.087 and 0.110 with the three-V and four-V flame holders, respectively, at an altitude of 26,000 feet and an indicated airspeed of 160 miles per hour. At 26,000 feet and 200 miles per hour, the ram Jet could not be operated with the two-V or four-V flame holder over a range of fuel-air ratios sufficiently wide for comparison. No attempt was made to operate the ram jet with the three-V flame holder at this condition. Reducing the indicated airspeed at 26,000 feet from 200 to 160 miles per hour resulted in smooth combustion for eaoh flame-holder configuration. Ingeneral, increasingthe flame-holder area resulted in an increased operating range of fuel-air ratio for smooth combustion.

The ram Jet cooled properly at all operating conditions for each of the three flame-holder configurations. Maximum combustion-ohamber-wall temperatures were obtained at an altitude of 1500 feet and were 410°, 382°, and 350° F for the two-V, three-V, and four-V flame holders, respectively. An increase in altitude resulted in a decrease in combustion-chamber-wall temperature.

At no time did the tufts mounted on the diffuser walls indicate any apparent combustion forward of the flame holder.

The starting characteristics of the ram Jet with eaoh flame-holder configuration are given in table I. For the determination of the ignition point, constant indicated airspeed and altitude were maintained, the spark was turned on, and the fuel flow was increased until ignition occurred. The fuel-air ratio at whloh ignition occurred is defined as the ratio of the fuel flow at ignition to the engine air flow as measured without combustion. At and above an altitude of 16,000 feet, the ram Jet oould not be started at an indicated airspeed of 200 miles per hour. The indicated airspeeds given at and above

16,000 feet are therefore approximately the maximum airspeeds at which ignition could be initiated. by the shielded spark plug. For each flame holder, increasing the altitude increased the value of the fuel-air ratio at whioh ignition occurred and deoreased the value of maximum indicated airspeed at which ignition was possible.

The two-V flame holder initiated combustion at a leaner fuel-air ratio than did the three-V and four-V flame holders at a given altitude and airspeed (table I). Combustion could also be initiated at a maximum altitude of 28,000 feet with the two-V flame holder (indicated airspeed, 105 to 115 mph), as compared with 25,300 feet with the three-V flame holder and 22,500 feet with the four-V flame holder. In general, inoreasing the flame-holder area increased the value of fuel-air ratio at whioh ignition occurred and deoreased the maximum altitude at which ignition was possible for a given indicated airspeed.

The effects of fuel-air ratio on combustion efficiency are shown in figure 4 for the two-V, three-V, and four-V flame holders with measured $\frac{p_2-p_4}{q_2}$ values (without combustion) of 2.3, 2.6, and 3.1, respectively, at altitudes of 1500, 6000, 16,000 and 26,OCC feet and given airspeeds. The value of combustion-chamber-inlet velocity is given for each data point and the average value of ambient inlet-air temperature is given for each curve. At all altitudes, the peak in the combustion-efficiency curve occurs at slightly lower values of fuel-air ratio for the two-V flame holder than for the three-8 flame holder and the peak efficiency for the three-V flame holder occurs at lower values of fuel-air ratio than for the four-V flame holder. For each flame holder, increasing the altitude resulted in a peak combustion effioienoy at higher values of fuel-air ratio. The highest combustion effioiencles for all the flame holders ooourred at the low altitudes; in general, an increase in altitude resulted in a decrease in combustion efficiency. This decrease is attributed to the combined effects of a decrease in air pressure, air temperature, and fuel pressure, which resulted in a decrease in at&cation of the fuel and penetration of the fuel particles in the air stream.

Of the three flame holders investigated, slightly higher combustion efficiencies occurred at all altitudes with the three-V flame holder, and the two-V flame holder produced higher efficiencies than did the four-V flame holder. The combustion efficiency for the three-V flame holder varied from a maximum of 82 percent at 1500 feet to 39 percent at 26,000 feet, compared with a variation from 81 to 31 percent for the two-V flame holder and a variation from 75 to 31 percent for the

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four-V flame holder. The ability of the three-V flame holder to produce higher combustion efficiencies is shown in figure 4(d) for an altitude of 26,000 feet, where at stoichiometric mixture (fuel-air ratio, 0.067) a value of 39 percent was obtained as compared with 31 percent for the two-V flame holder and 28 percent for the four-V flame holder. The lower values of combustion efficiency obtained with the four-V flame holder may be part4 attributed to the lower ambient-air temperature encountered with the four-V flame holder, inasmuch as reference 3 shows that when other factors were held constant a decrease in combustion-air temperature resulted in a decrease in combustion efficiency. Combustion-efficiency data presented for the three-V flame holder at 6000 feet, however, were taken from five flights in which the ambient inlet-air temperature varied from 22° to 51° F. Because these data could be plotted as a single curve, the small variation in ambient inlet-air temperature for the three flame holders was believed to have a negligible effeot on combustion effioienoy.

The tailed symbols in figure 4 indicate the fuel-air ratio at which blow-out occurred, which is defined as the ratio of fuel flow at blow-out to the engine air flow immediately preceding blow-out. At altitudes of 1500 and 6000 feet, the ram Jet could be operated at lower values of fuel-air ratio before encountering blow-out with either the three-V or four-V flame holder than with the two-V flame holder (figs. 4(a) and 4(b)). The two-Vflame holderwas unable to maintain stable combustion at low values of fuel-air ratio and combustion efficiency, and blow-out was sudden and unexpected. At altitudes of 16,000 and 26,000 feet, the four-V flame holder operated at lower fuel-air ratios than the two-V and three-V flame holders (figs. 4(c) and 4(d)).

The effeots of fuel-air ratio on gas total-temperature ratio are given in figure 5 for the three flame holders for altitudes of 1500, 6000, 16,000, and 26,000 feet. Inasmuchas gas total-temperature ratfo is a function of both combustion efficiency and fuel-air ratio, the trends observed in figure 4 are not necessarily repeated in figure 5. The highest temperature ratio (7.10) occurred at 6000 feet with the three-V flame holder at a fuel-air ratio of 0.082 (fig 5(b)). The highest temperature ratio for the two-V flame holder (6.60) occurred at 16,000 feet at a fuel-air ratio of 0.088 (fig. 5(c)) and the highest value for the four-V flame holder (6.60) occurred at 1500 feet at a fuel-air ratio of 0.075 (fig. 5(a)). In general, increasing the flame-holder area resulted in peak values of gas total-temperature ratio at higher values of fuel-air ratio for a given altitude condition.

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The effect of fuel-air ratio on the net-thrust coefficient for the two-V, three-v, and four-V flame holders at altitudes of 1500, 6000, 16,000, and 26,000 feet is presented in figure 6. In general, the highest net-thrust coefficients occurred with the two-V flame holder and the lowest coefficients ooourred with the four-V flame holder at any given altitude and fuel-air ratio. Apparently the lover value of $\frac{p_2-p_4}{q_2}$ (without combustion) resulting from the lower ratio of flame-holder area to ocmbustion-chamber area of the two-V flame holder more than offset its slightly lower values of gas total-temperature ratio and therefore resulted in generally higher values of net-thrust coefficient. From the data presented in figure 6, it is apparent that as the fuel-air ratio increased from the lean blow-out value a rapid increase in net-thrust coefficient ooourred, followed by a gradual leveling of the curve. At the low altitudes (1500 and 6000 feet), the net-thrust-coefficient curves begin to level off at fuel-air ratios from 0.06 to 0.07 and operation at richer mixtures did not result in any appreoiable Increase in net-thrust coefficient. The ranges of net-thrust coefficients for each flame holder were approximately the same for eaoh altitude, except at 26,000 feet where the reduction in indicated airspeed of from 200 to 160 miles per hour resulted in lower values of flight Mach number and therefore lower net-thrust coefficients. In general, increasing the flame-holder area increased. the value of fuel-air ratio at which the maximum net-thrust coefficient ooourred.

SUMMARY OF RESULTS

From the flight investigation conducted on a rectangular ram jet incorporating three different flame-holder configurations, over a range of pressure altitudes from 1500 to 28,000 feet, combustion-chamber-inlet velocities from 50 to 125 feet per second, and fuel-air ratios from 0.017 to 0.120, the following results were obtained:

1. Of the flame holders investigated, slightly higher peak combustion efficiencies were obtained at all altitudes with the three-V flame holder and the two-V flame holder resulted in slightly higher values than the four-V flame holder. The altitude effects on the maximum oombustion efficiencies η_b for eaoh flame holder, the corresponding value8 of fuel-air ratio f/a and of $\frac{p_2-p_4}{q_2}$ (without combustion) (where p_2 is static pressure at diffuser outlet, p_4 is static pressure at combustion-chamber outlet, and q_2 is dynamic pressure at diffueer outlet) are as follows:

Altitude (ft)	Flame holder	$\frac{p_2-p_4}{q_2}$	'lb	$\frac{f}{a}$
1,500	Two-v	2.3	81	0.050
	Three-V	2.6	82	.058
	Four-V	3.1	75	.062
6,000	Two-V	2.3	72	0.052
	Three-V	2.6	75	.060
	Four-V	3.1	62	.067
16,000	Two-v	2.3	60	0.063
	Three-V	2.6	62	,067
	Four-V	3.1	45	,073
26,000	Two-V	2.3	31	0.070
	Three-V	2.6	39	.072
	Four-V	3.1	31	.085

2. The highest gas total-temperature ratio (7.10) was obtained at 6000 feet with the three-V flame holder operating at a fuel-air ratio of 0.082. The highest temperature ratio for the two-V flame holder (6.60) occurred at 16,000 feet at a fuel-air ratio of 0.088 and the highest value for the four-V flame holder (6.60) occurred at 1500 feet at a fuel-air ratio of 0.075.

3. The highest net-thrust coefficients occurred with the two-V flame holder and the lowest values occurred with the four-V flame holder at any given altitude and fuel-air ratio. The lower value of $\frac{p_2-p_4}{q_2}$ (without combustion) resulting from the lower ratio of flame-holder area to combustion-chamber area of the two-V flame holder more than offset Its slightly lower values of gas total-temperature ratio and therefore resulted in generally higher values of net-thrust coefficients.

4. In general, increasing the flame-holder area increased the value of fuel-air ratio at which Ignition occurred and decreased the maximum altitude at which ignition was possible for a given airspeed. At an indicated airspeed of approximately 115 miles per hour, combustion could be Initiated at 28,000 feet with the two-V flame holder, as oompared with 25,300 feet with the three-V flame holder and 22,500 feet with the four-V flame holder.

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1. Black, Dugald O., and Messing, Wesley E.: Test-Stand Investigation of a Rectangular Ram-Jet Engine. NACA RM No. E7D11, 1947.

2. Messing, Wesley E., and Black, Dugald O.: Subsonic Flight Investigation of Rectangular Ram Jet over Range of Altitudes. NACA RM No. E7H26, 1948.

3. Cervenka, A. J., and Miller, R. C.: Effect of Inlet-Air Parameters on Combustion Limit and Flume Length in 8-Inch-Diameter Ram-Jet Combustion Chamber. NACA RM No. E8C09, 1948.

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TABLE I. - STARTING CHARACTERISTICS OF RAM JET

WITH THREE FLAME-HOLDER CONFIGURATIONS

Altitude (ft)	Indicated airspeed (mph)	Fuel-air ratio
Two-V flame holder		
1,500	200	0.019
6,000	200	.027
6,000	200	.022
16,000	160	.047
21,500	115	.045
22,000	115	.057
24,400	115	.078
27,200	120	.097
27,500	120	.098
27,600	115	,086
28,000	112	,094
Three-V flame holder		
1,500	200	0.017
6,000	200	.036
6,000	200	.037
16,000	160	.052
20,100	120	.077
33,000	110	.080
23,850	118	.093
25,300	105	.094
Four-V flame holder		
1,500	200	0.028
3,000	200	,036
6,000	200	.038
1tl,000	160	.038
11,000	160	.044
16,000	160	.052
18,000	125	.067
22,500	115	.078

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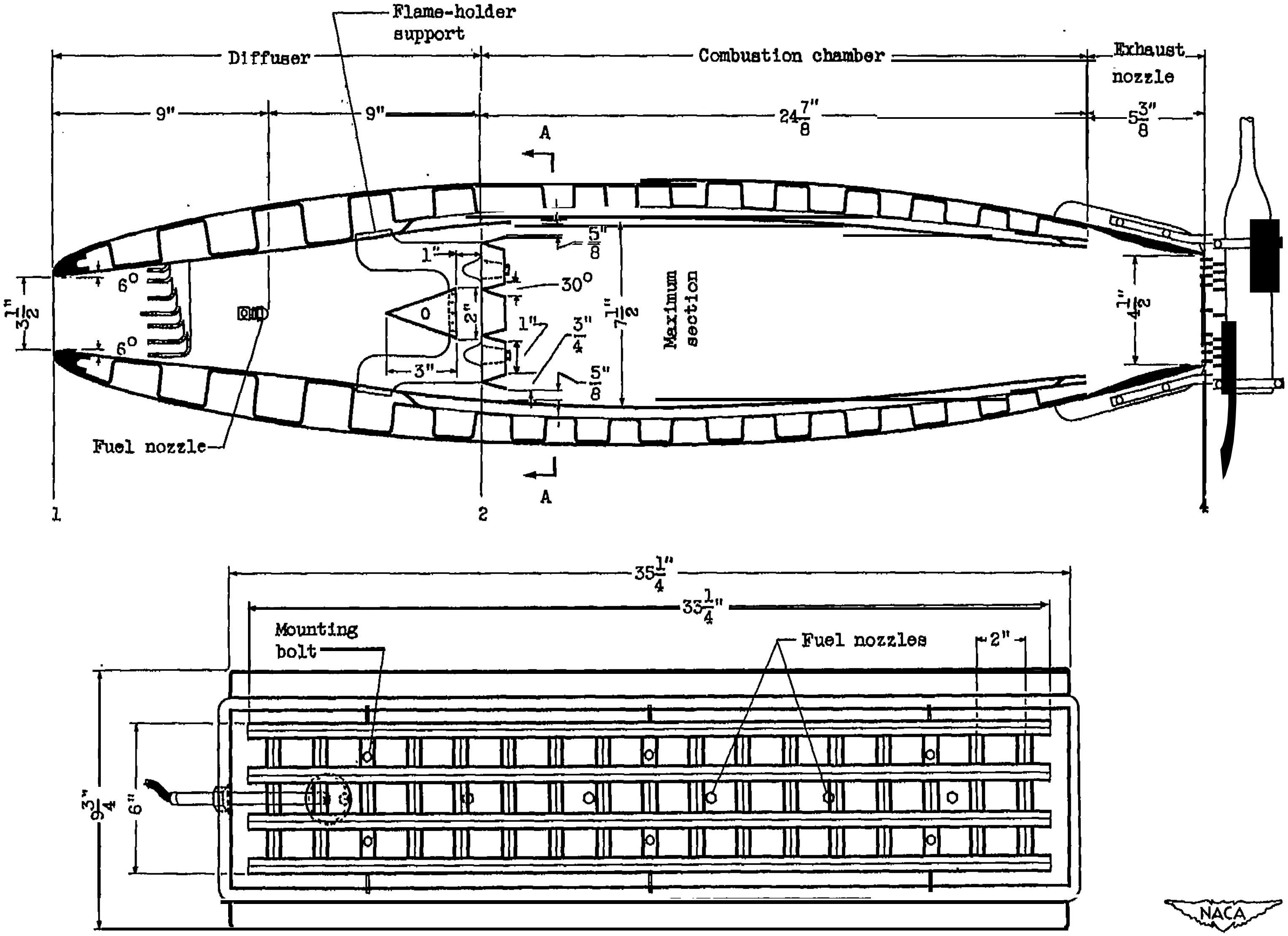
Figure 1. - Rectangular ram jet installed beneath airplane fuselage.



Section A-A

Figure 1. - Schematic diagram of rectangular ram Jet incorporating four-V gutter-type flame holder.

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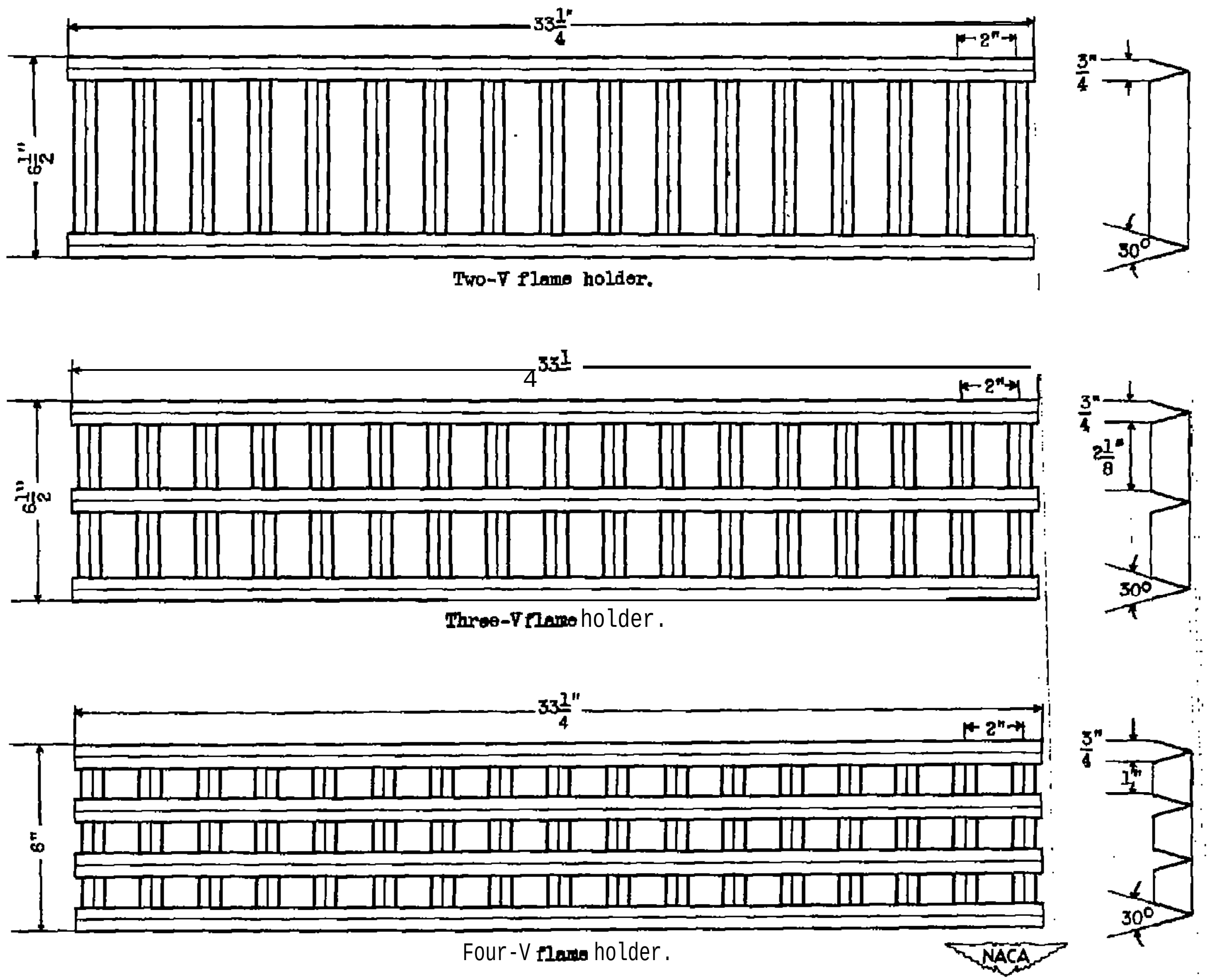
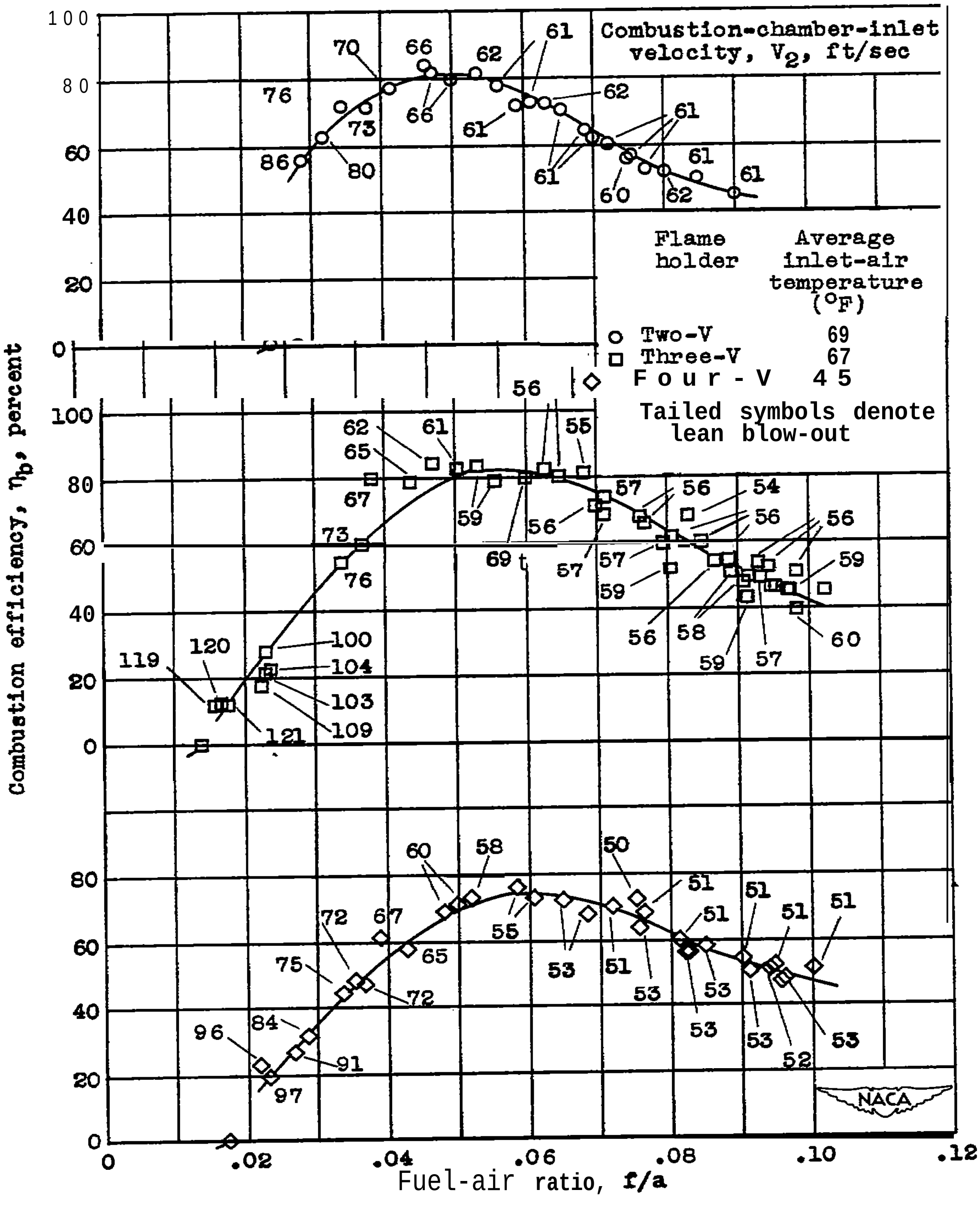


Figure 5. - Various flame-holder configurations investigated with rectangular ram jet.



(a) Pressure altitude, 1500 feet; indicated airspeed, 200 miles per hour.

Figure 4. - Effect of fuel-air ratio on combustion efficiency for rectangular ram jet incorporating three flame-holder configurations.

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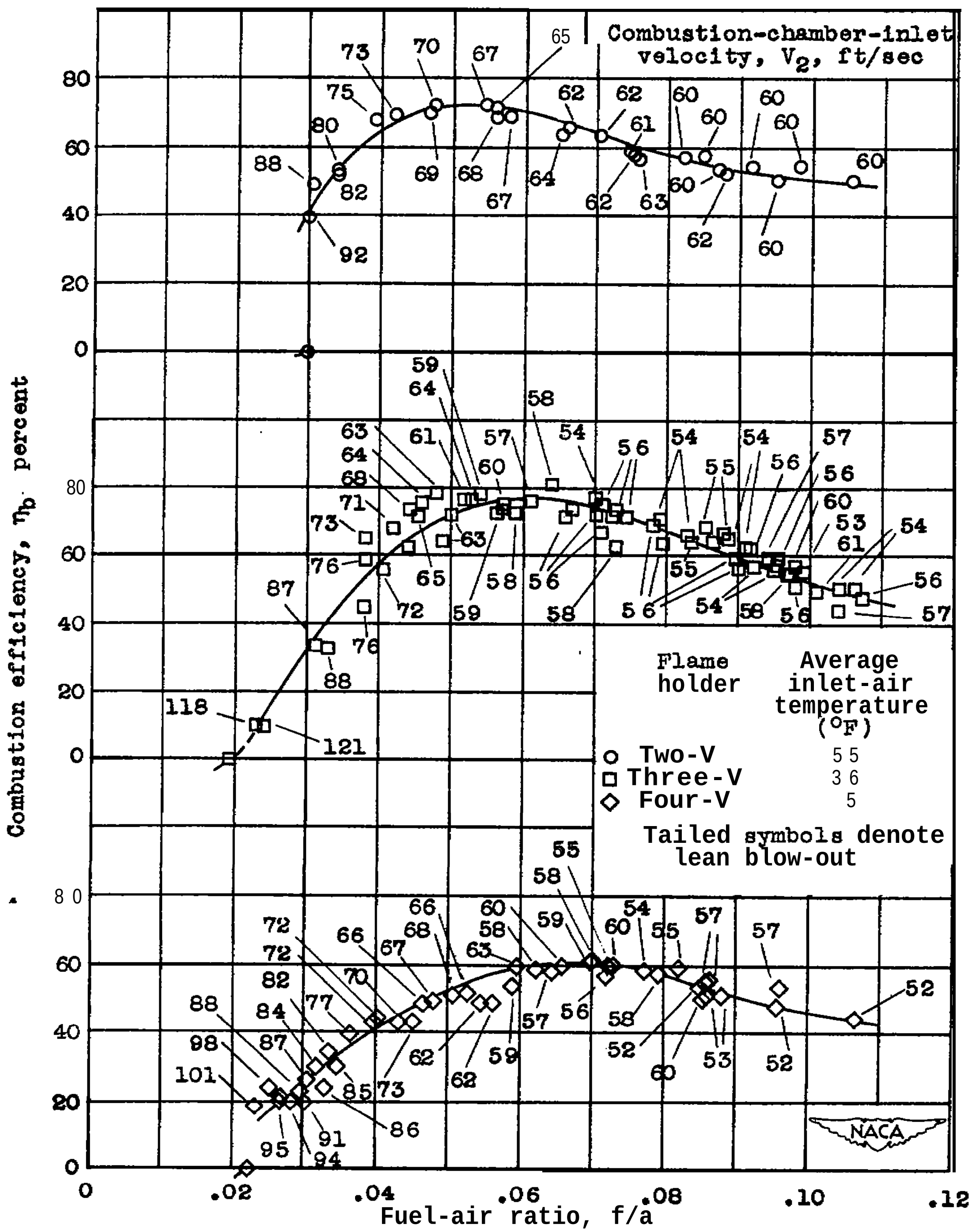

(b) Pressure altitude, 6000 feet; indicated airspeed, 200 miles per hour.

Figure 4. - Continued. Effect of fuel-air ratio on combustion efficiency for rectangular ram jet Incorporating three flame-holder configurationa.

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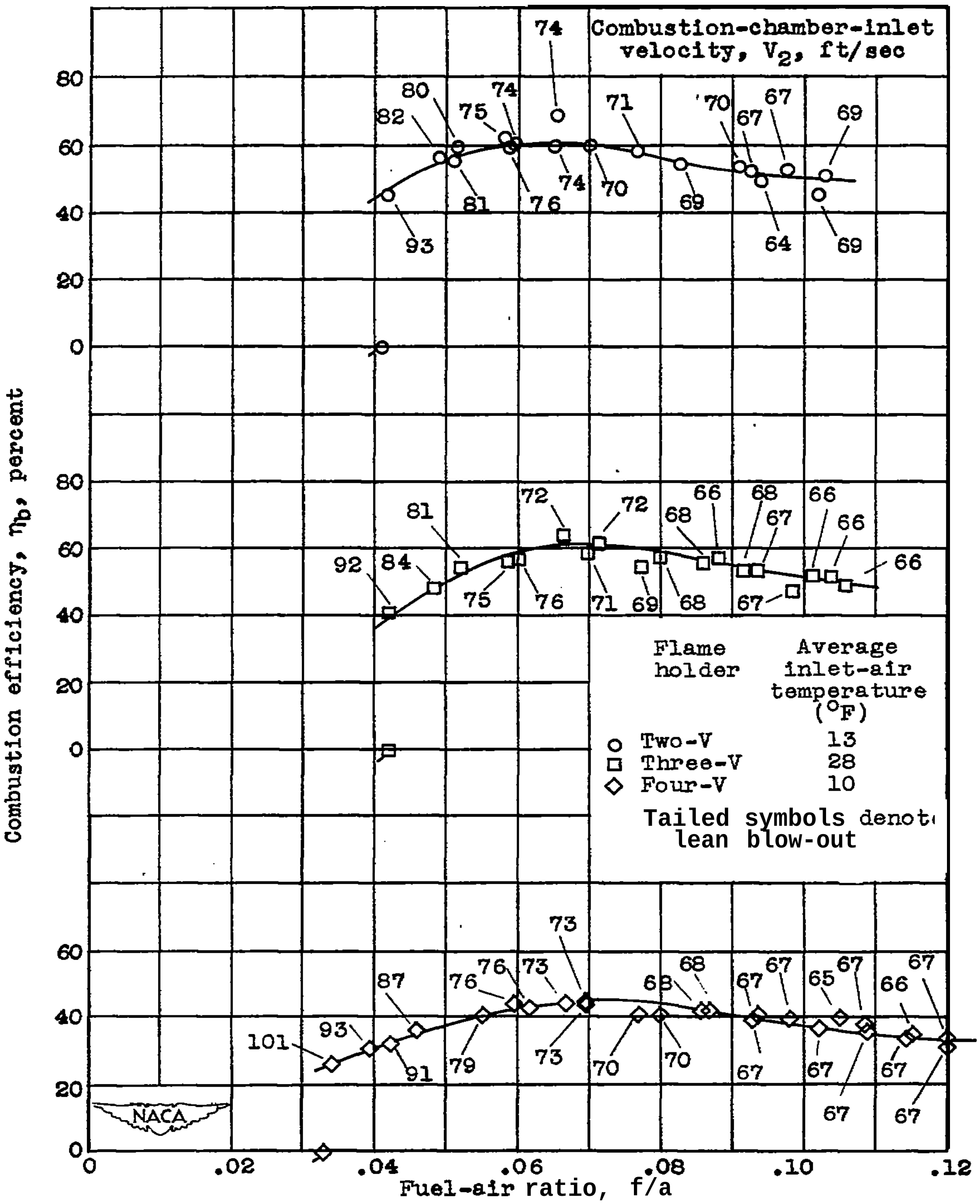

(c) Pressure altitude, 16,000 feet; indicated airspeed, 200 miles per hour.

Figure 4. - Continued. Effect of fuel-air ratio on combustion efficiency for rectangular ram jet incorporating three flame-holder configurations.

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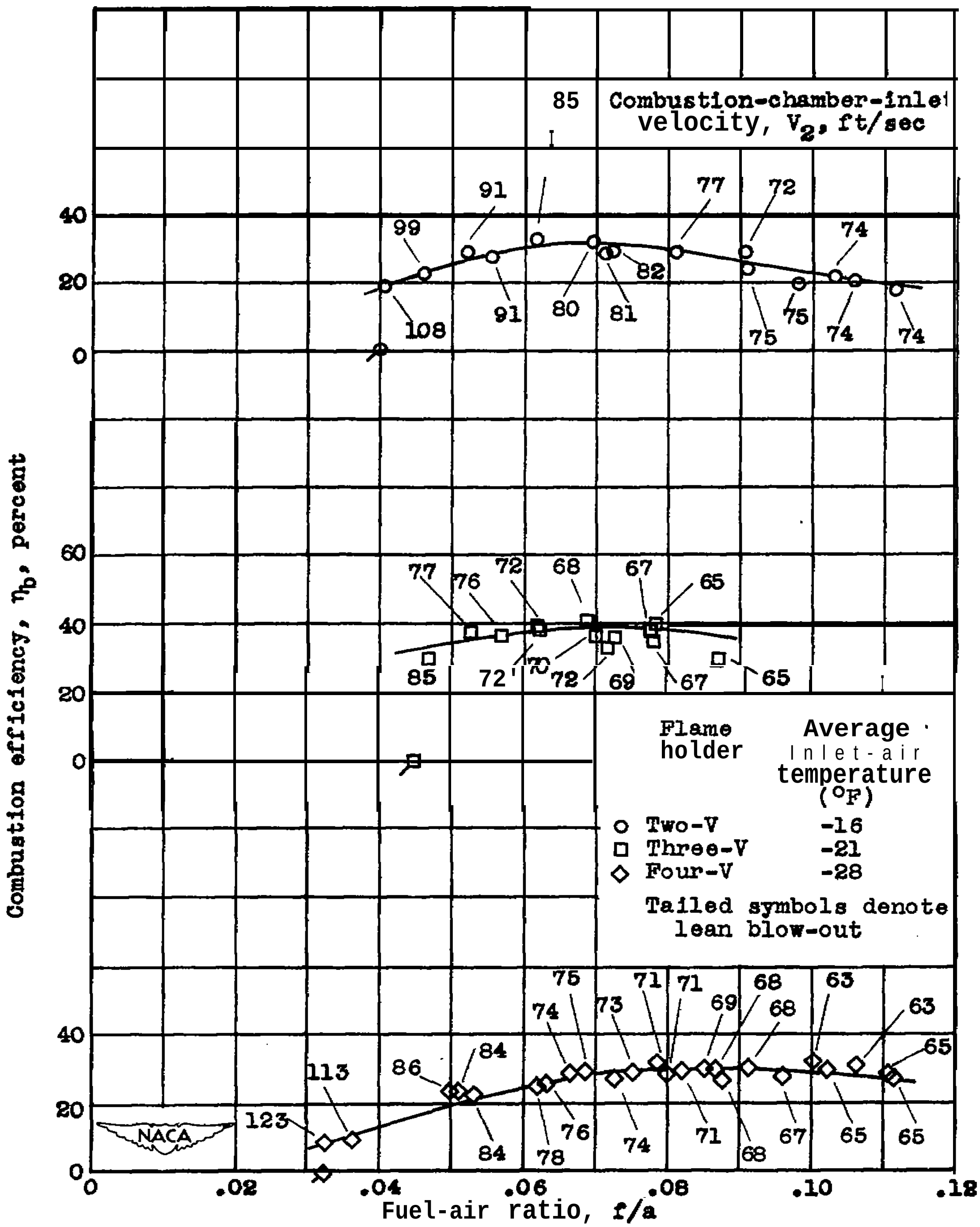

(d) Pressure altitude, 26,000 feet; Indicated airspeed, 160 miles per hour.

Figure 4. - Concluded. Effect of fuel-air ratio on combustion efficiency for rectangular ram jet incorporating three flame-holder configurations.

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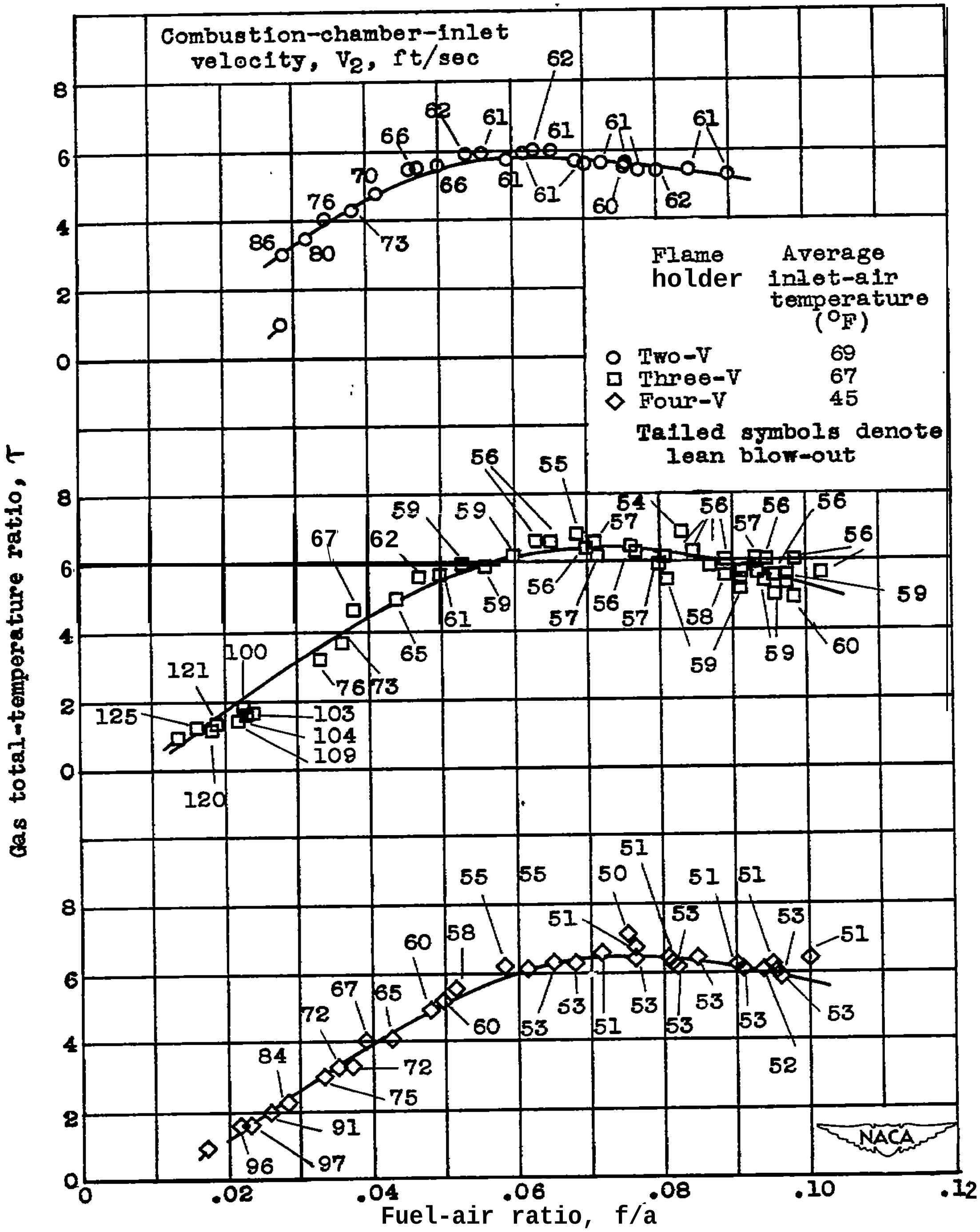

(a) Pressure altitude, 1500 feet; indicated airspeed, 200 miles per hour.

Figure 5. - Effect of fuel-air ratio on gas total-temperature ratio for rectangular ram jet incorporating three flame-holder configurations.

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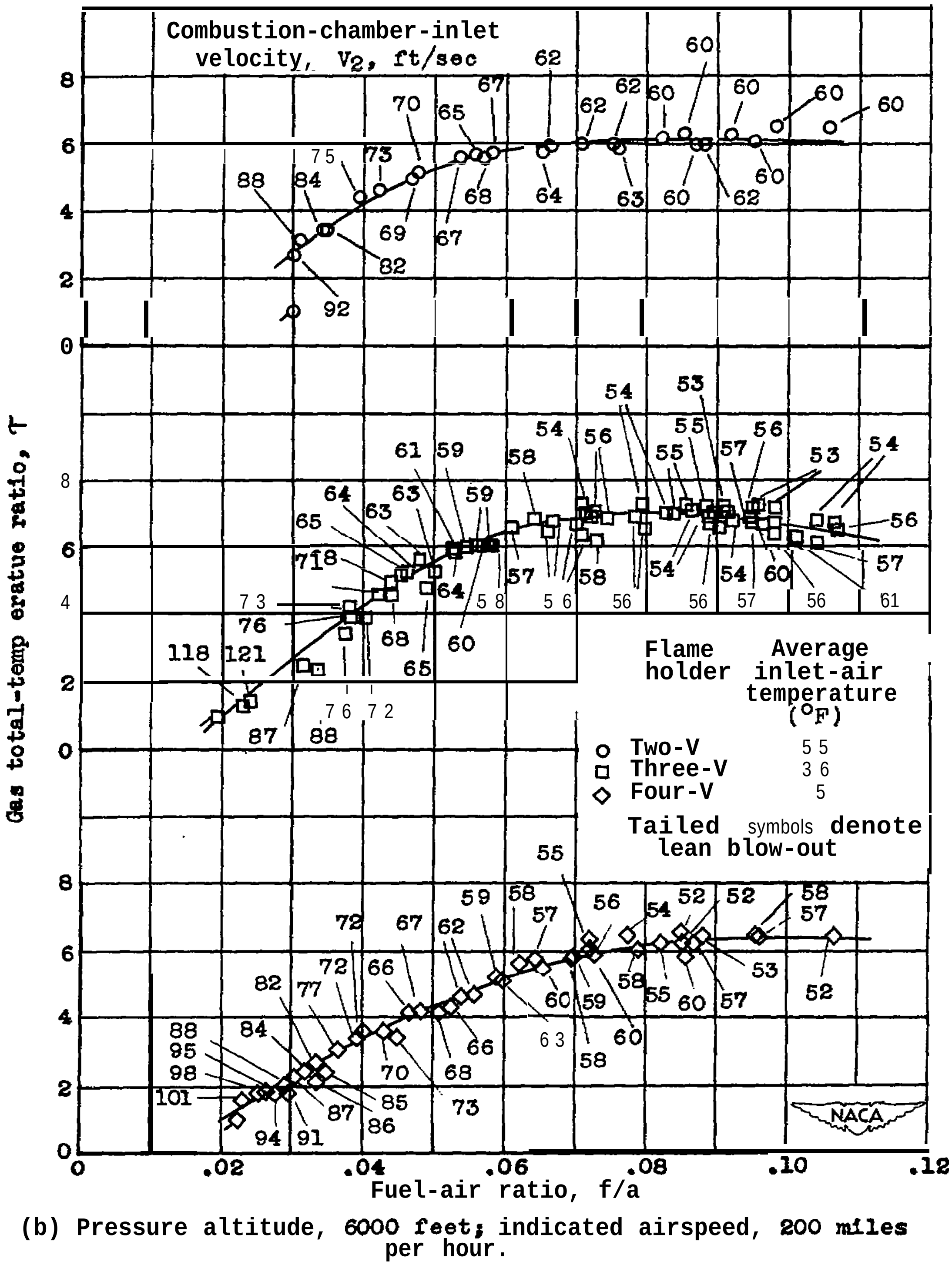

(b) Pressure altitude, 6000 feet; indicated airspeed, 200 miles per hour.

Figure 5. - Continued. Effect of fuel-air ratio on gas total-temperature ratio for rectangular ram jet incorporating three flame-holder configurations.

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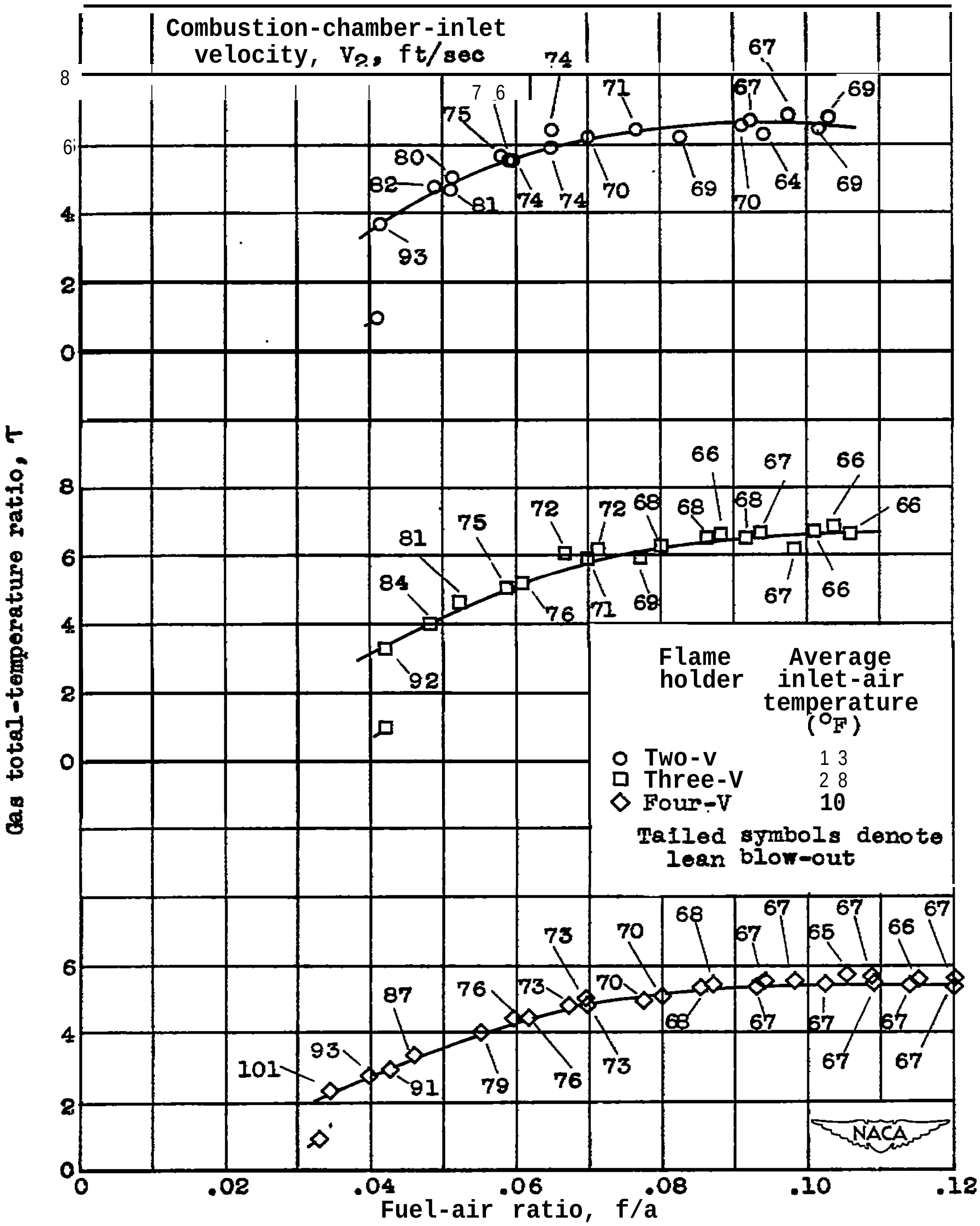

(c) Pressure altitude, 16,000 feet; indicated airspeed, 200 miles per hour.

Figure 5. - Continued. Effect of fuel-air ratio on gas total-temperature ratio for rectangular ram jet incorporating three flame-holder configurations.

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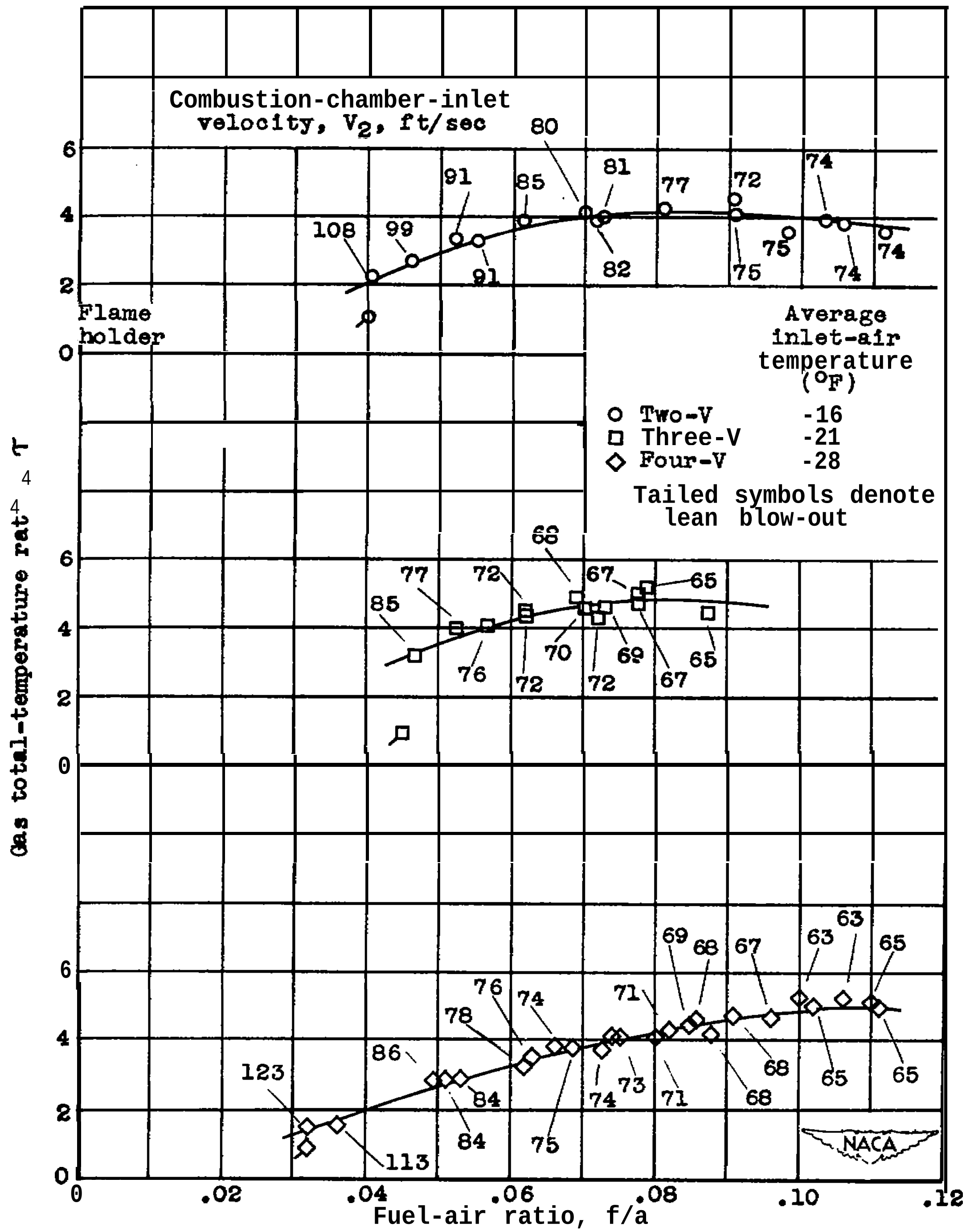

(d) Pressure altitude, 26,000 feet; indicated airspeed, 160 miles per hour.

Figure 5. - Concluded. Effect of fuel-air ratio on gas total-temperature ratio for rectangular ram jet incorporating three flame-holder configurations.

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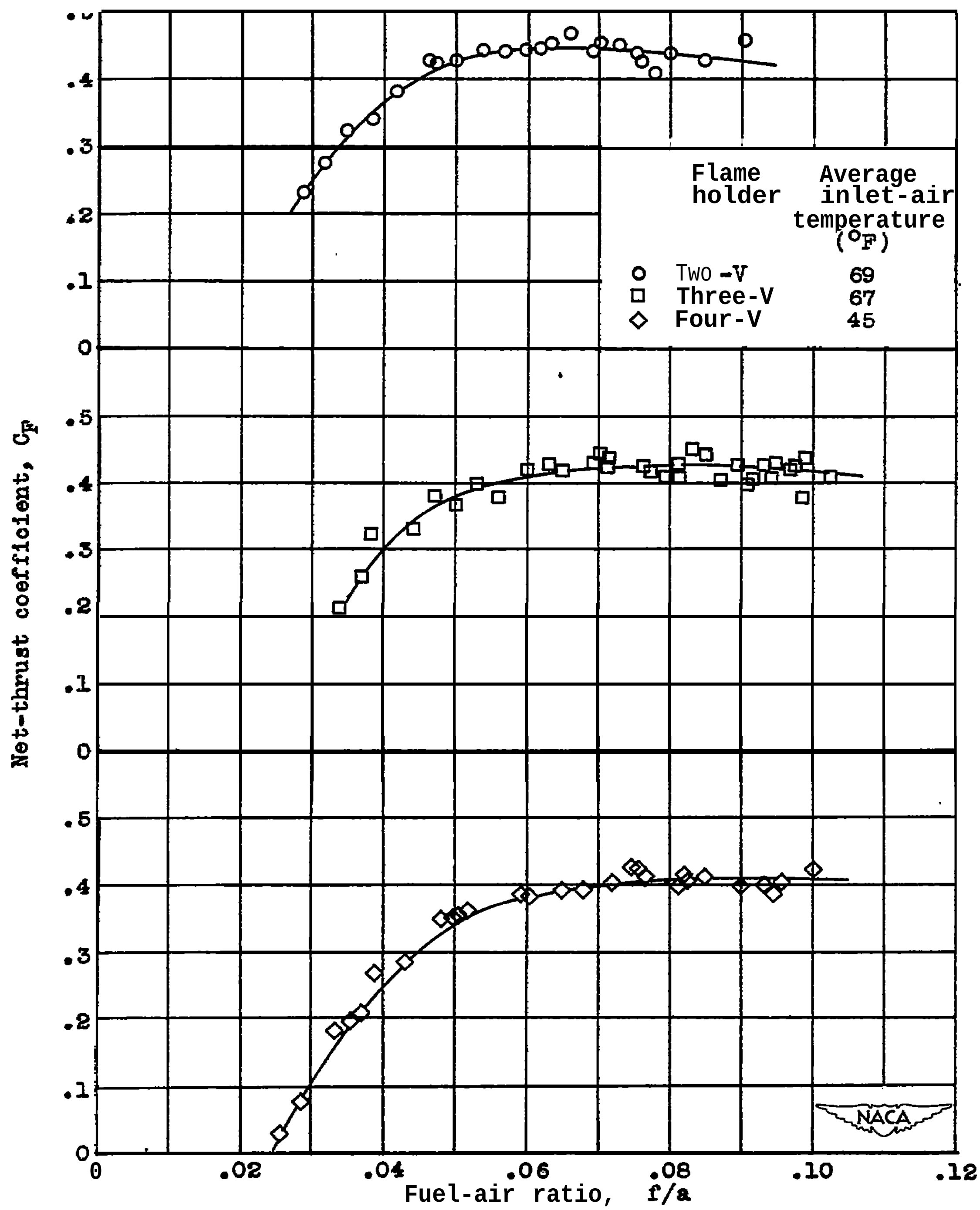
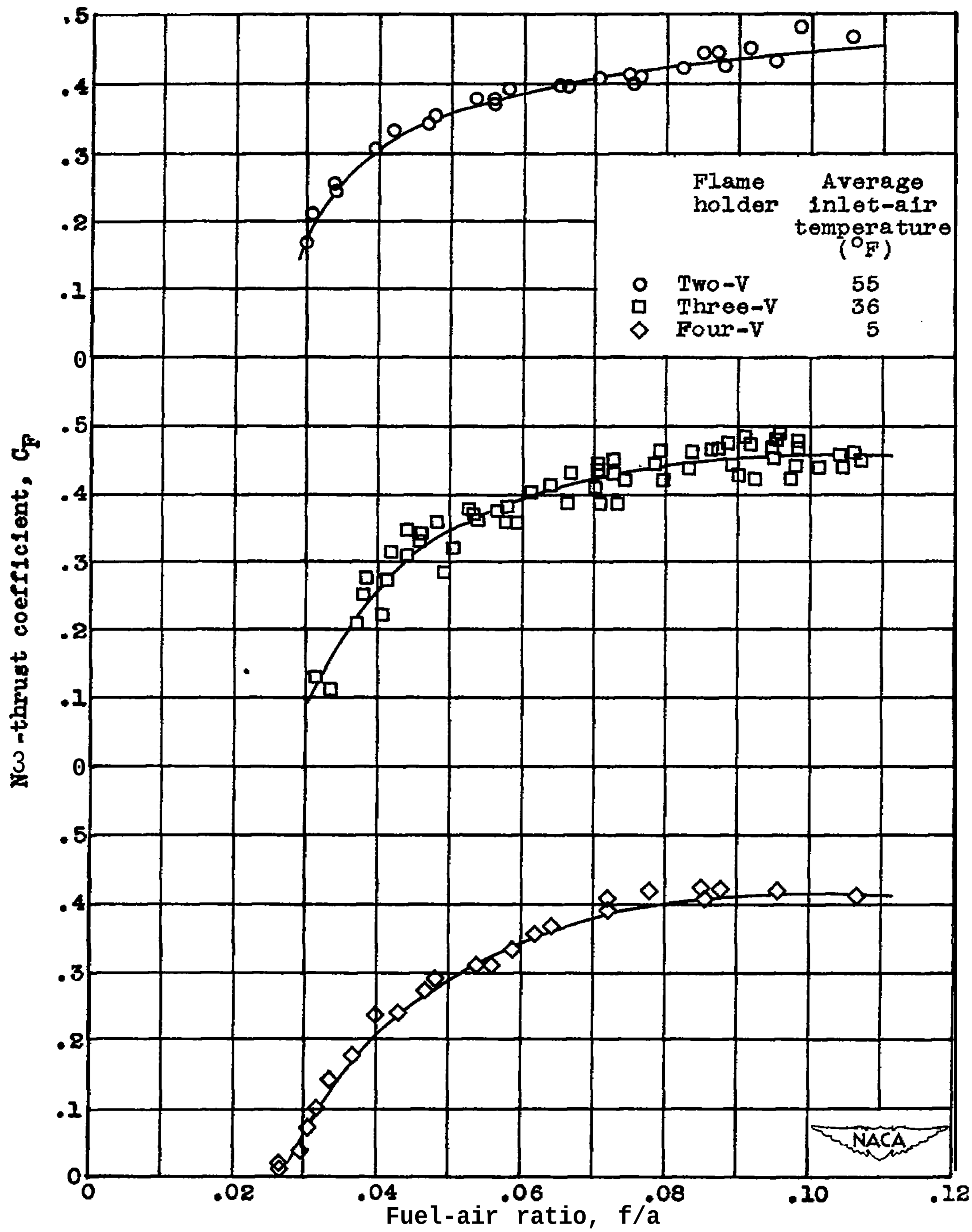


(a) Pressure altitude, 1600 feet; indicated airspeed, 200 miles per hour.

Figure 6. - Effect of fuel-air ratio on net-thrust coefficient for rectangular ram jet incorporating three flame-holder configurations.



(b) Pressure altitude, 6000 feet; indicated airspeed, 200 miles per hour.

Figure 6. - Continued. Effect of fuel-air ratio on net-thrust coefficient for rectangular ram jet incorporating three flame-holder configurations.

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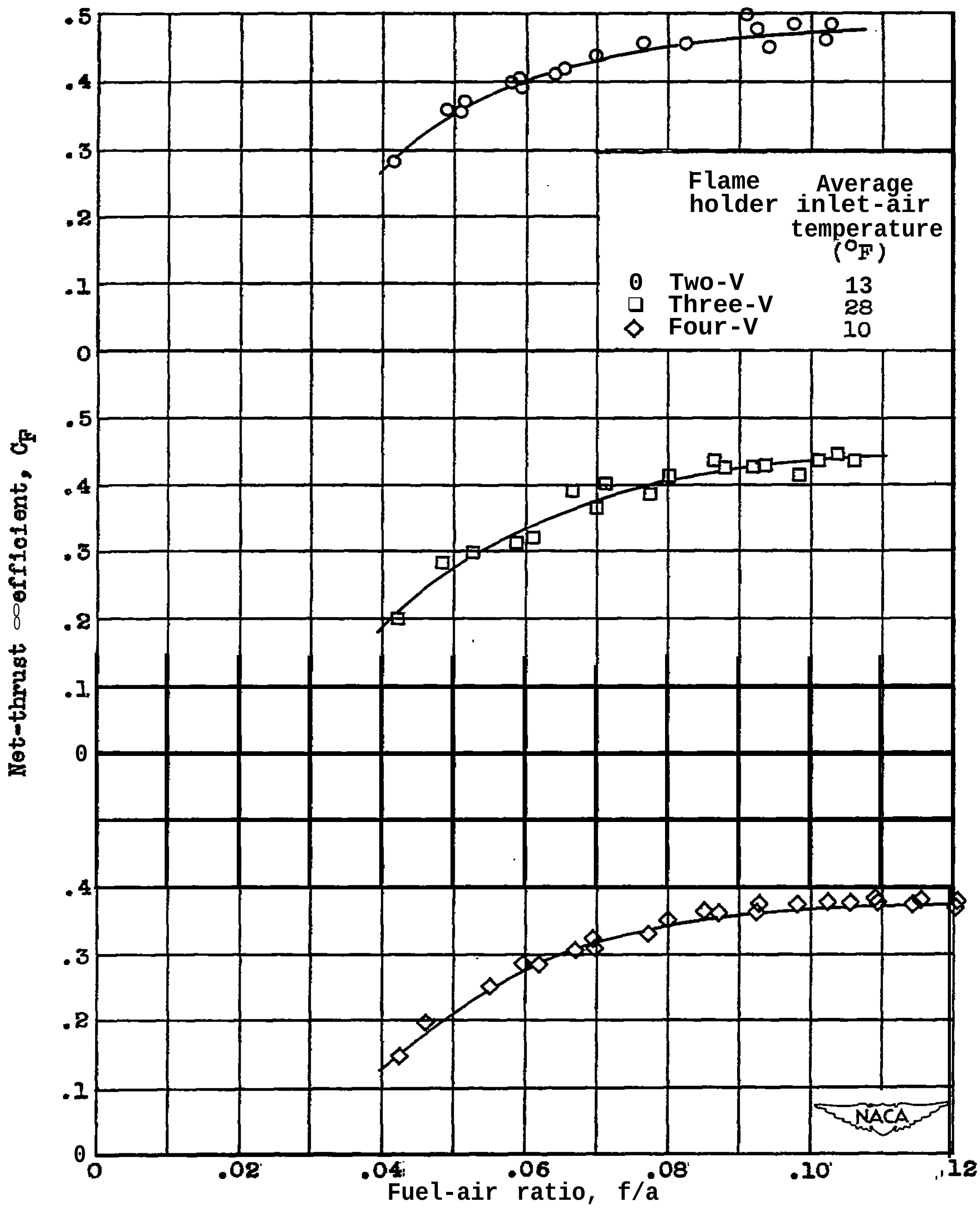

(c) Pressure altitude, 16,000 feet; indicated airspeed, 200 miles per hour.

Figure 6. - Continued. Effect of fuel-air ratio on net-thrust coefficient for rectangular ram jet incorporating three flame-holder configurations.

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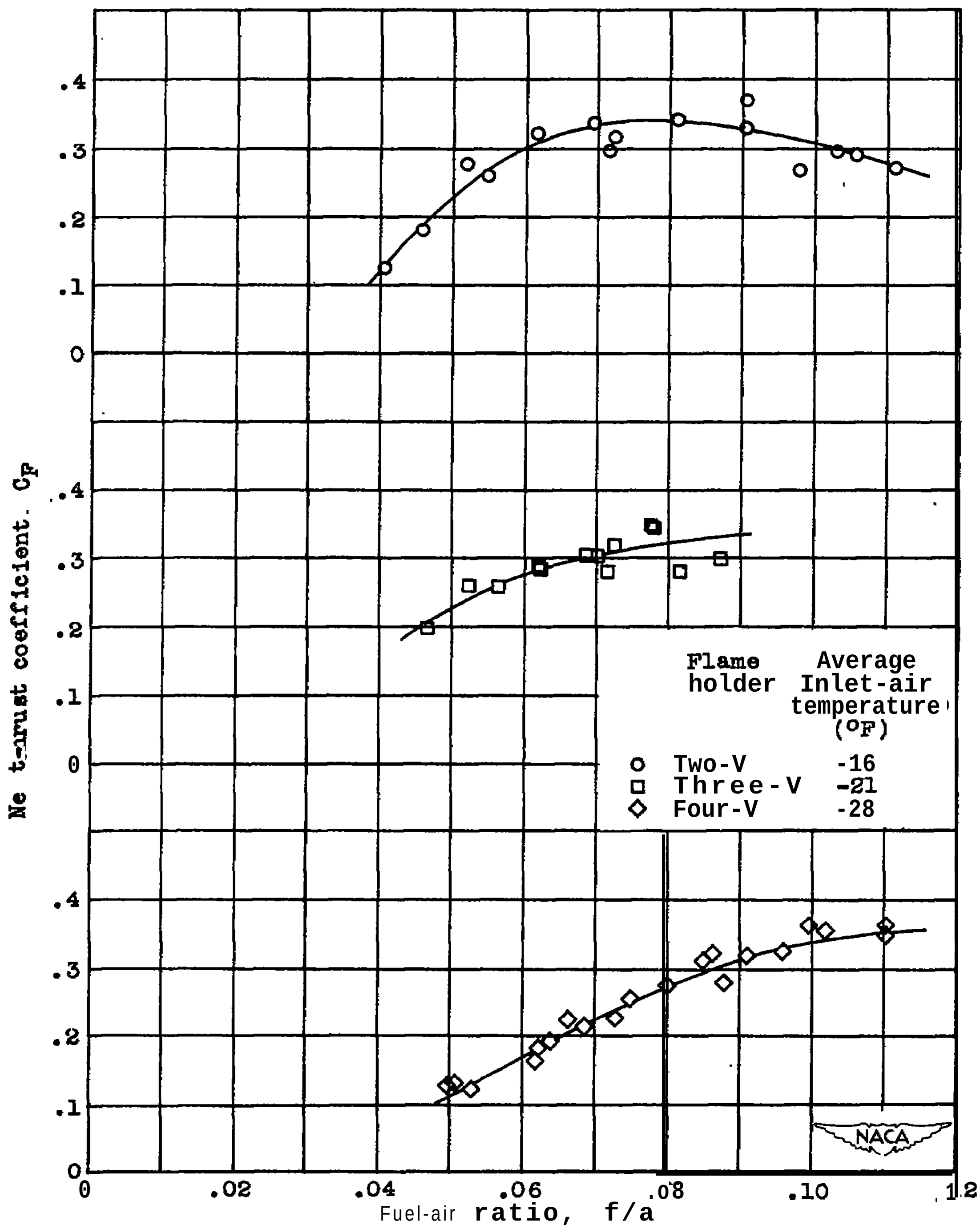

(d) Pressure altitude, 26,000 feet; indicated airspeed, 160 miles per hour.

Figure 6. - Concluded. Effect of fuel-air ratio on net-thrust coefficient for rectangular ram jet incorporating three flame-holder configurations.

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[redacted]